The Ground Based Gravitational Wave Observatory: from current to advanced

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Texas Symposium, Heidelberg

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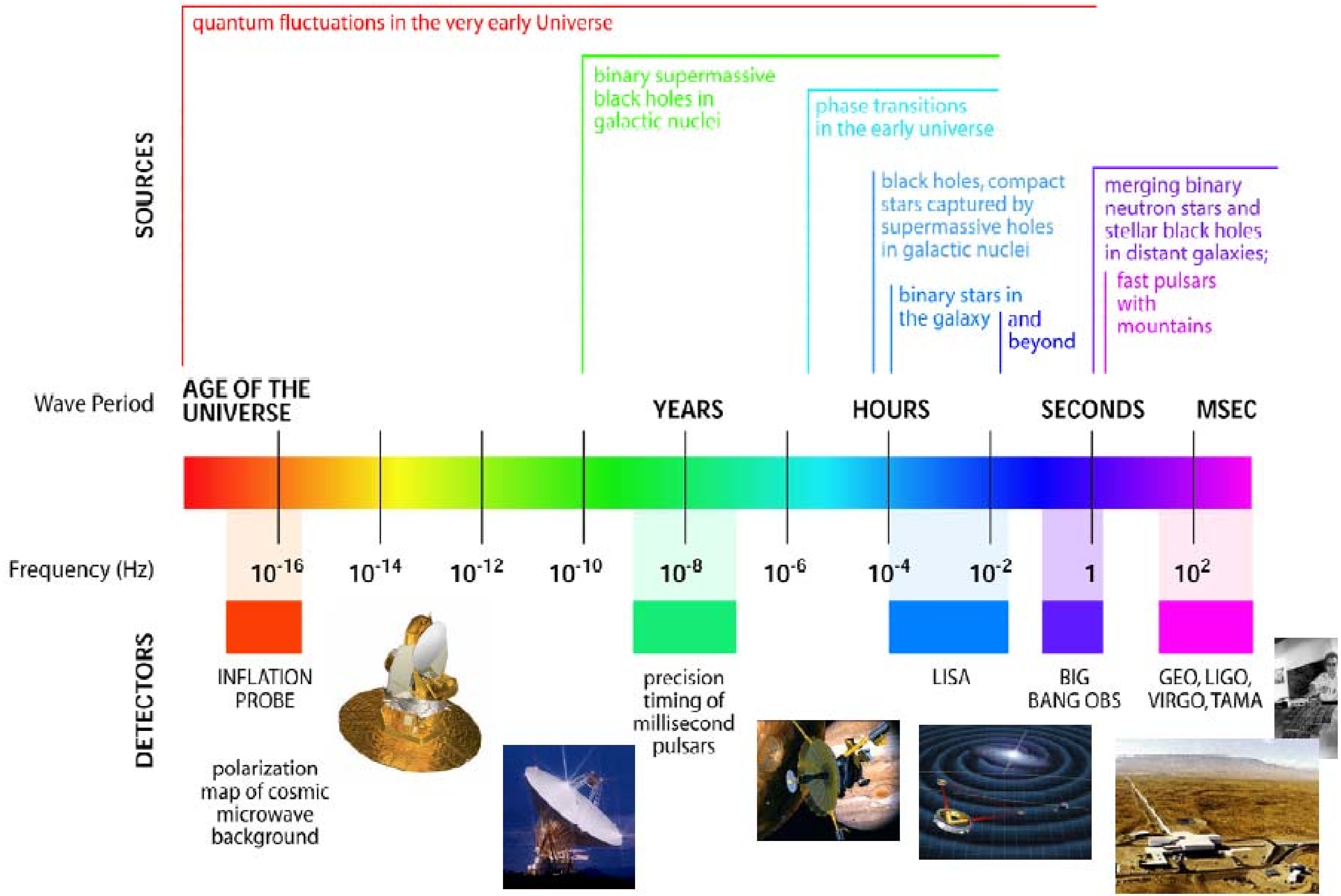
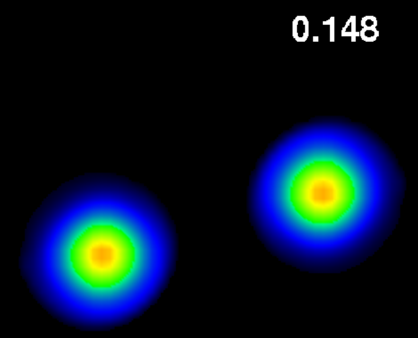
LSC

LIGO-G1001130

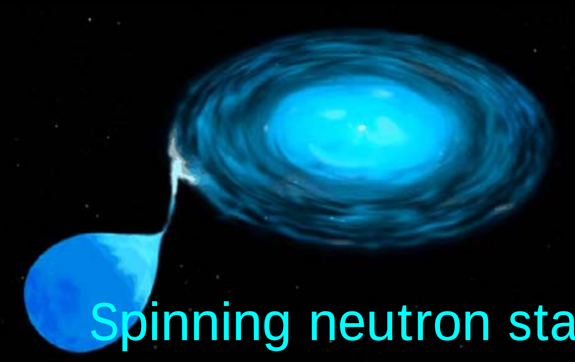
THE GRAVITATIONAL WAVE SPECTRUM



GW sources in ground-based detectors

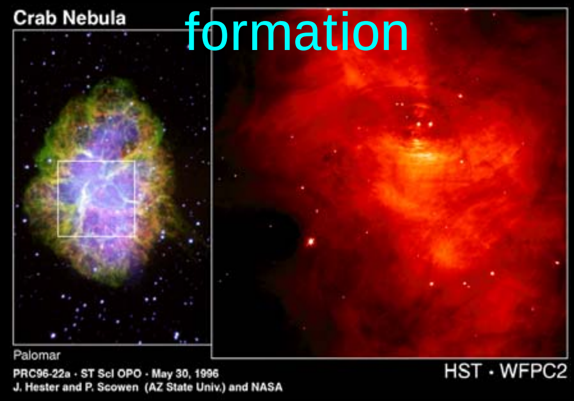


Binaries of black holes
and neutron stars



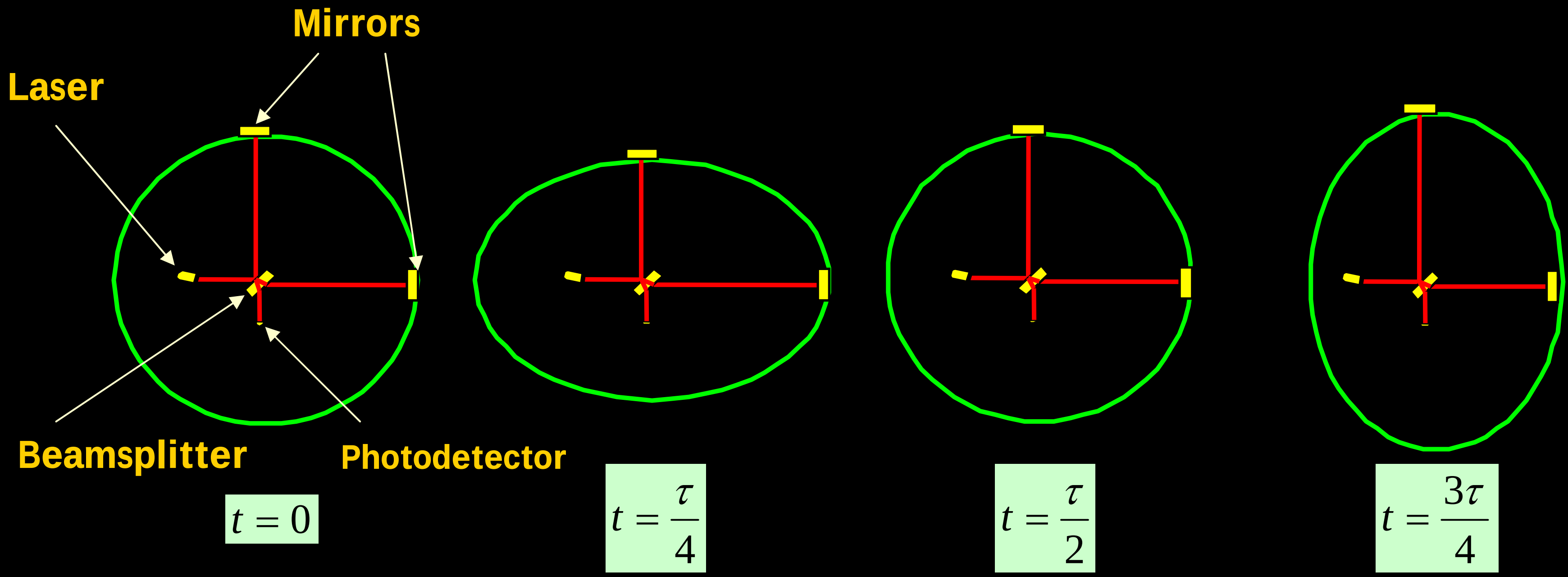
Spinning neutron stars
in X-ray binaries

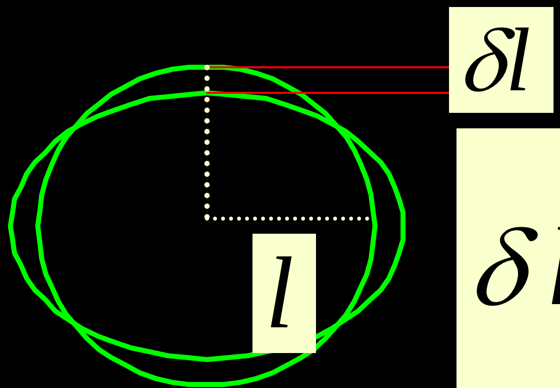
Supernovae and black hole
formation



Young neutron
stars

Operation of Interferometric Gravitational Wave Detectors





$$\delta l = \frac{h}{2} l$$

For Typical Astronomical sources

$$h = \frac{2 \delta l}{l} \leq 10^{-22}$$

Principal limitations to sensitivity

- Photon shot noise (improves with increasing laser power) and radiation pressure (becomes worse with increasing laser power)

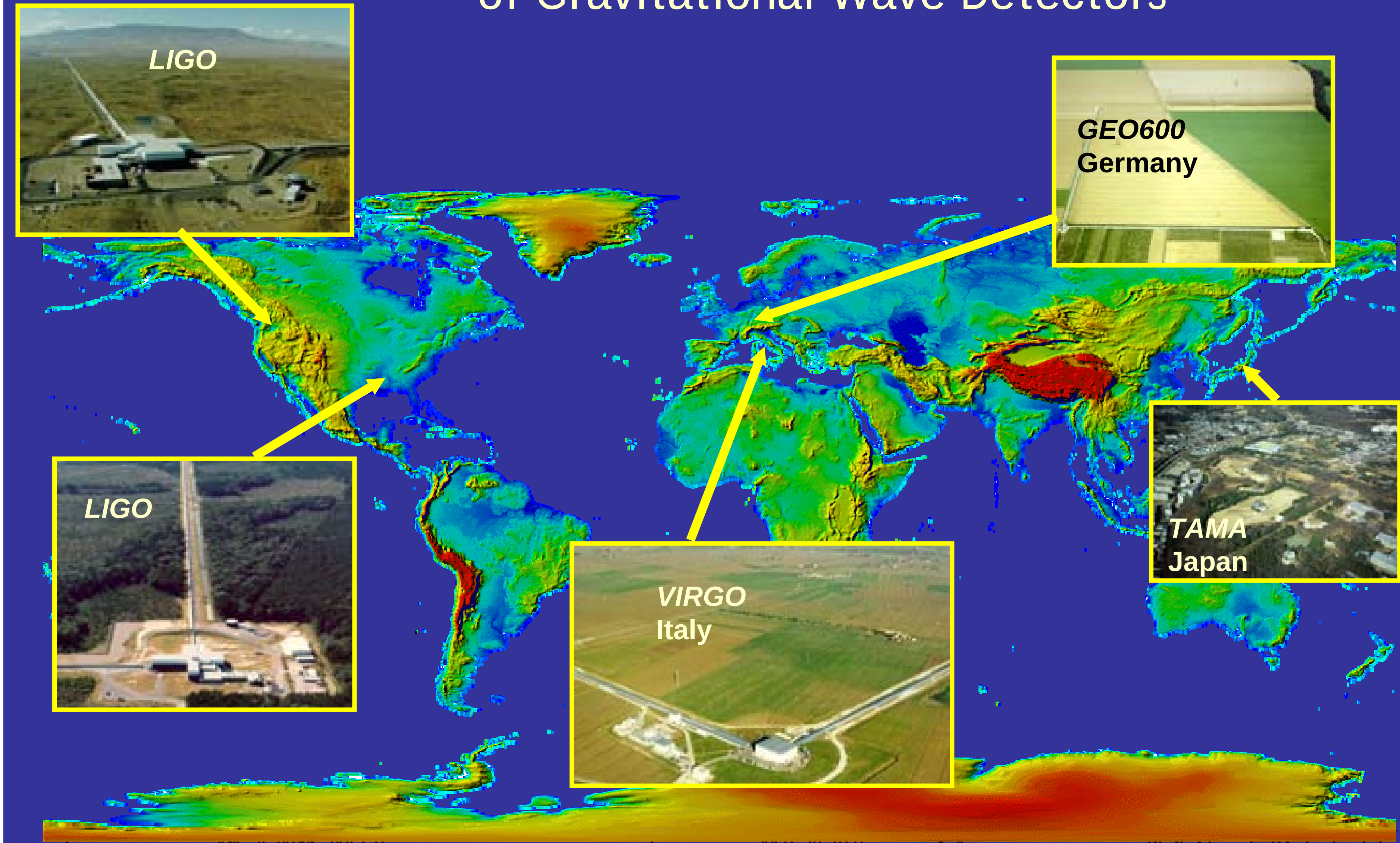
  There is an optimum light power which gives the same limitation expected by application of the Heisenberg Uncertainty Principle – the 'Standard Quantum limit'

- Seismic noise (relatively easy to isolate against – use suspended test masses)
- Gravitational gradient noise, – particularly important at frequencies below ~10 Hz
- Thermal noise – (Brownian motion of test masses and suspensions)

All point to long arm lengths being desirable

- **Global network of interferometers developed**

The Global Network of Gravitational Wave Detectors

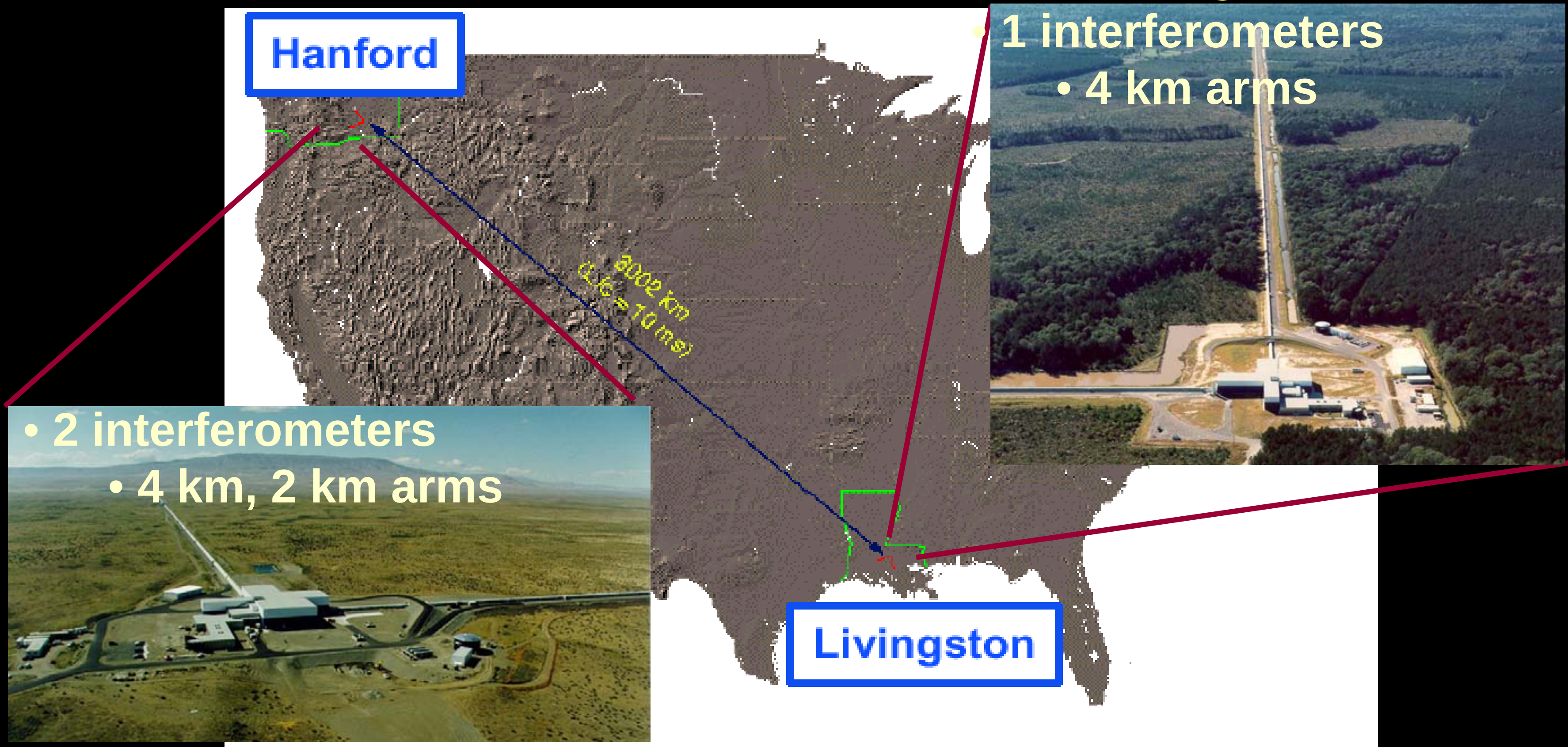


LIGO sites (US)

LIGO Observatories are operated by Caltech and MIT

LIGO Livingston Observatory

- 1 interferometers
  - 4 km arms

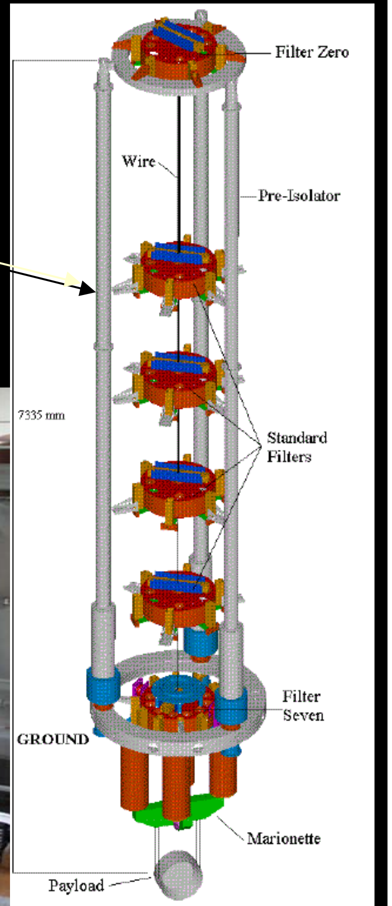


- 2 interferometers
  - 4 km, 2 km arms

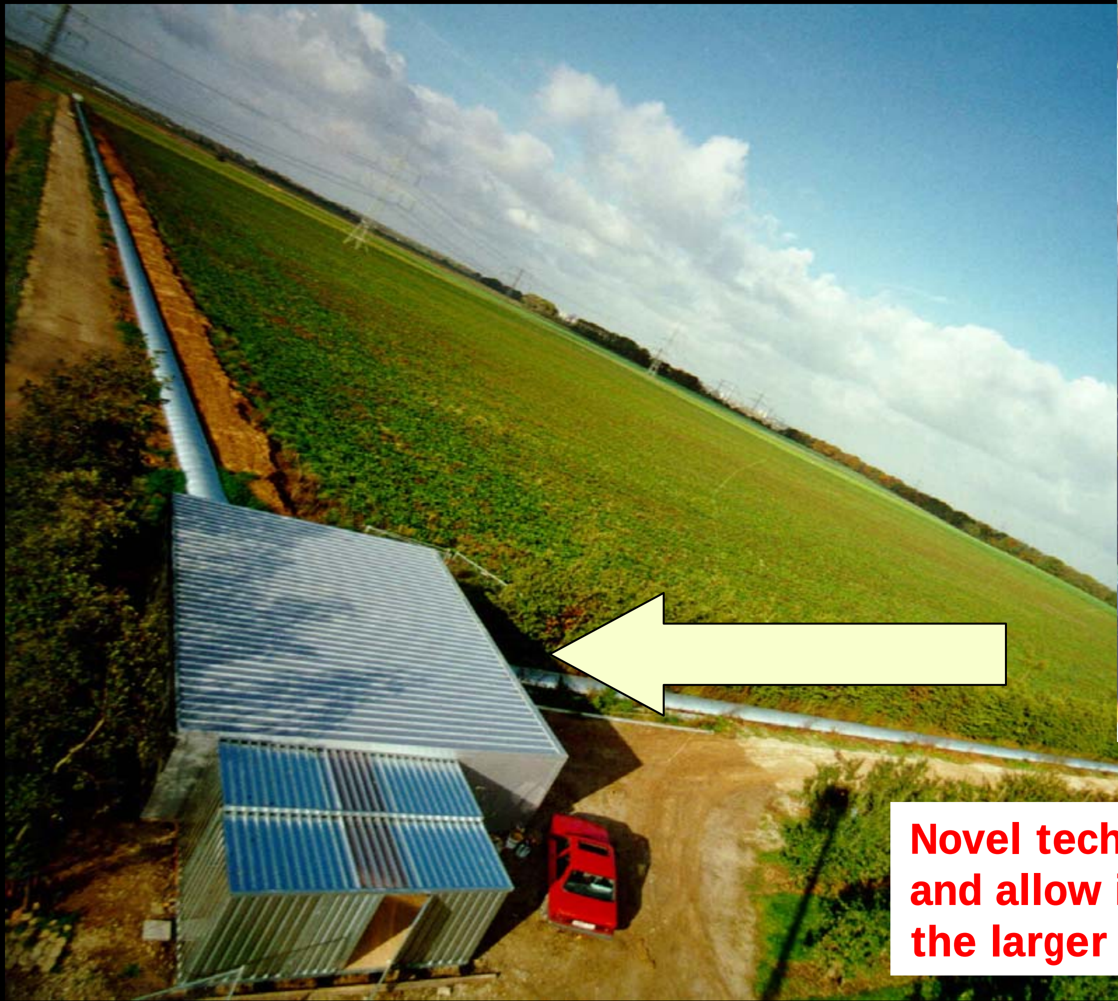
LIGO Hanford Observatory

VIRGO: 3 km armlength at Cascina near Pisa (France-Italy-Netherlands)

The 'Super Attenuator' filters the seismic noise above 4 Hz



GEO 600



Novel technologies make GEO unique and allow it to run in coincidence with the larger LIGO (and Virgo) instruments

Other Detectors and Developments – TAMA 300 and AIGO

TAMA 300 Tokyo
300 m arms

AIGO Gingin, WA
80 m arm test facility

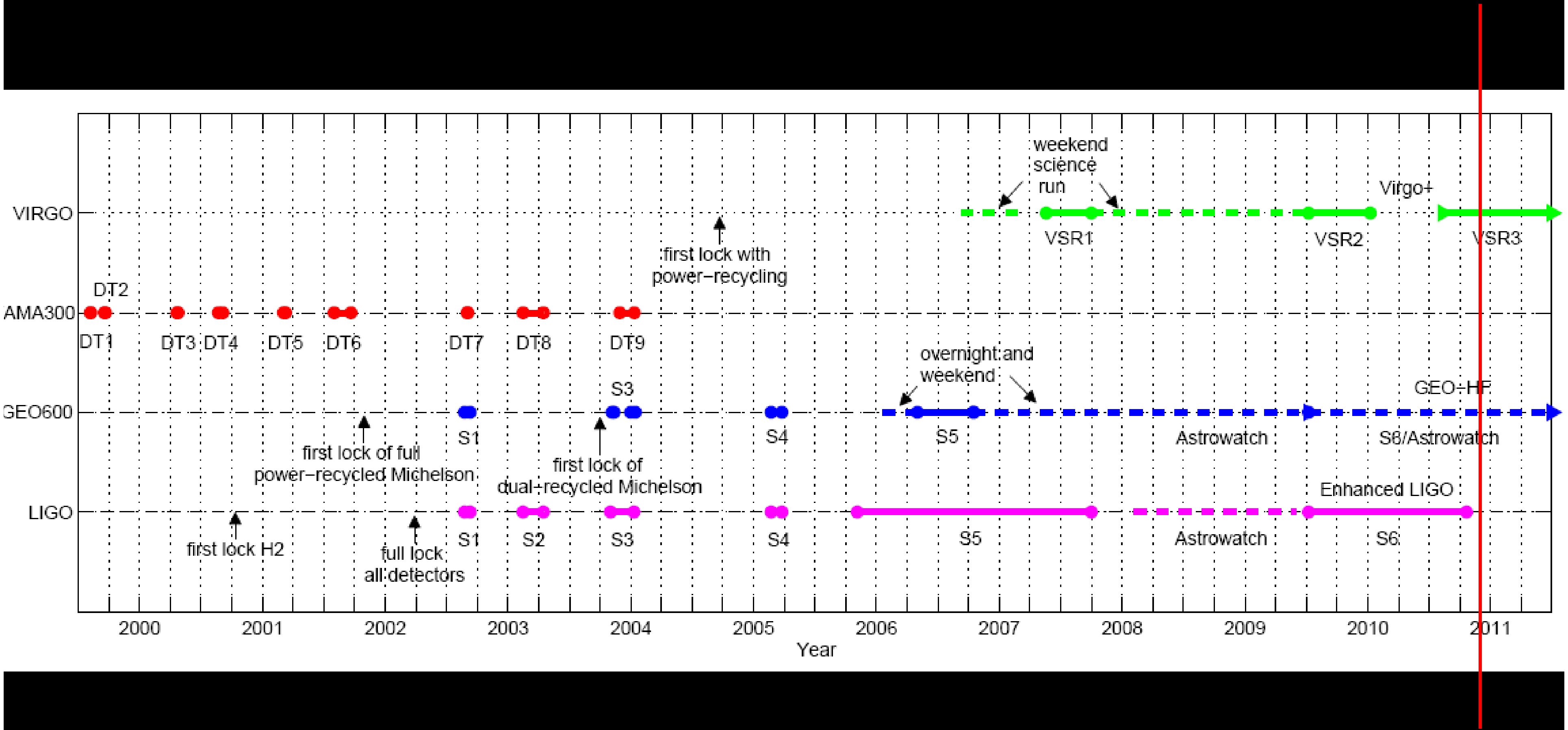
Collaborative approach

- The LIGO Scientific collaboration (LSC) includes > 500 people
- The LSC carries out a scientific program of instrument science and data analysis.
- The 3 LIGO interferometers and the GEO600 instrument are analysed as one data set

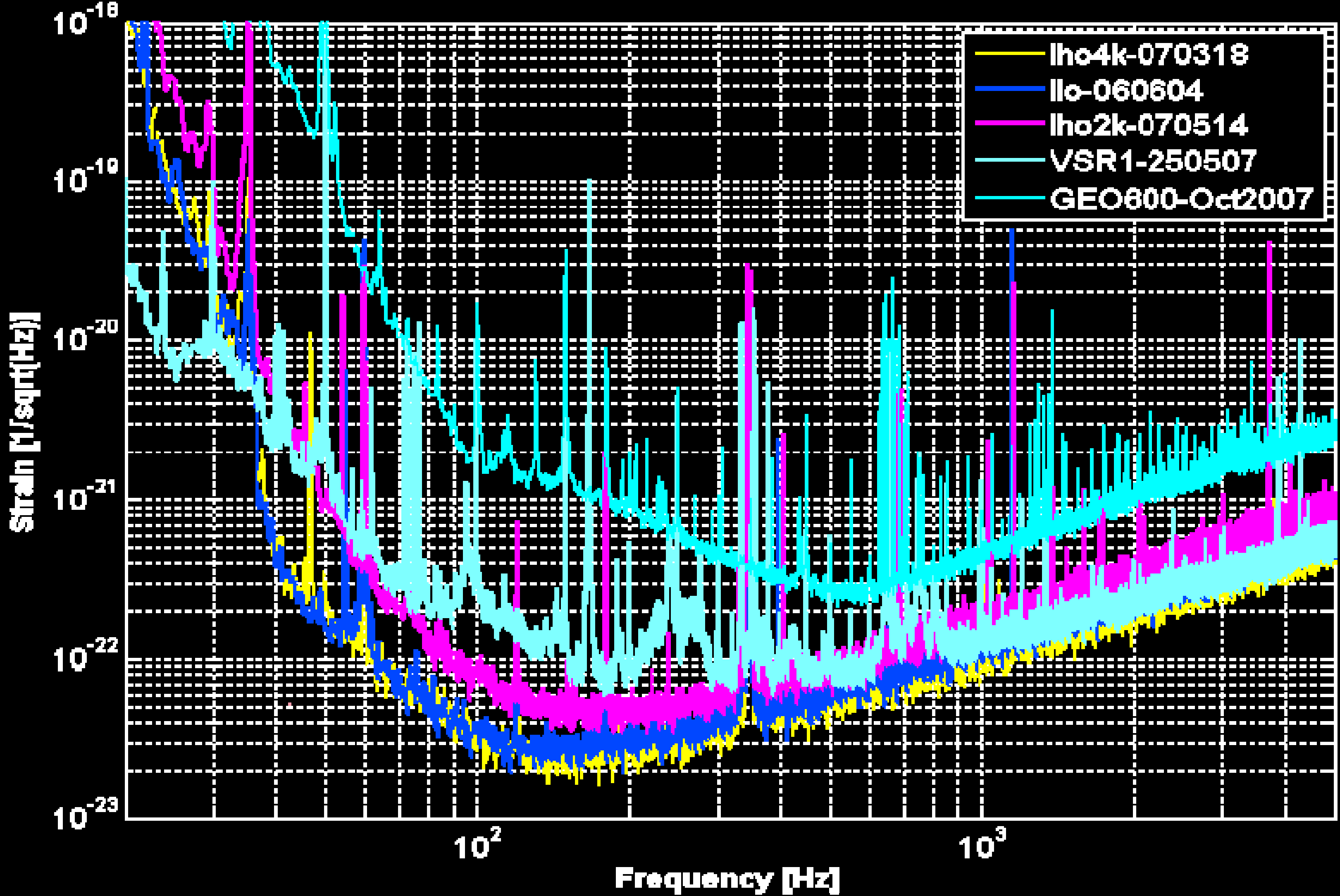
- LSC & Virgo signed a 'Memorandum of Understanding'
  - Joint data analysis
  - Increased science potential

  Joint run plan for the single, global GW network

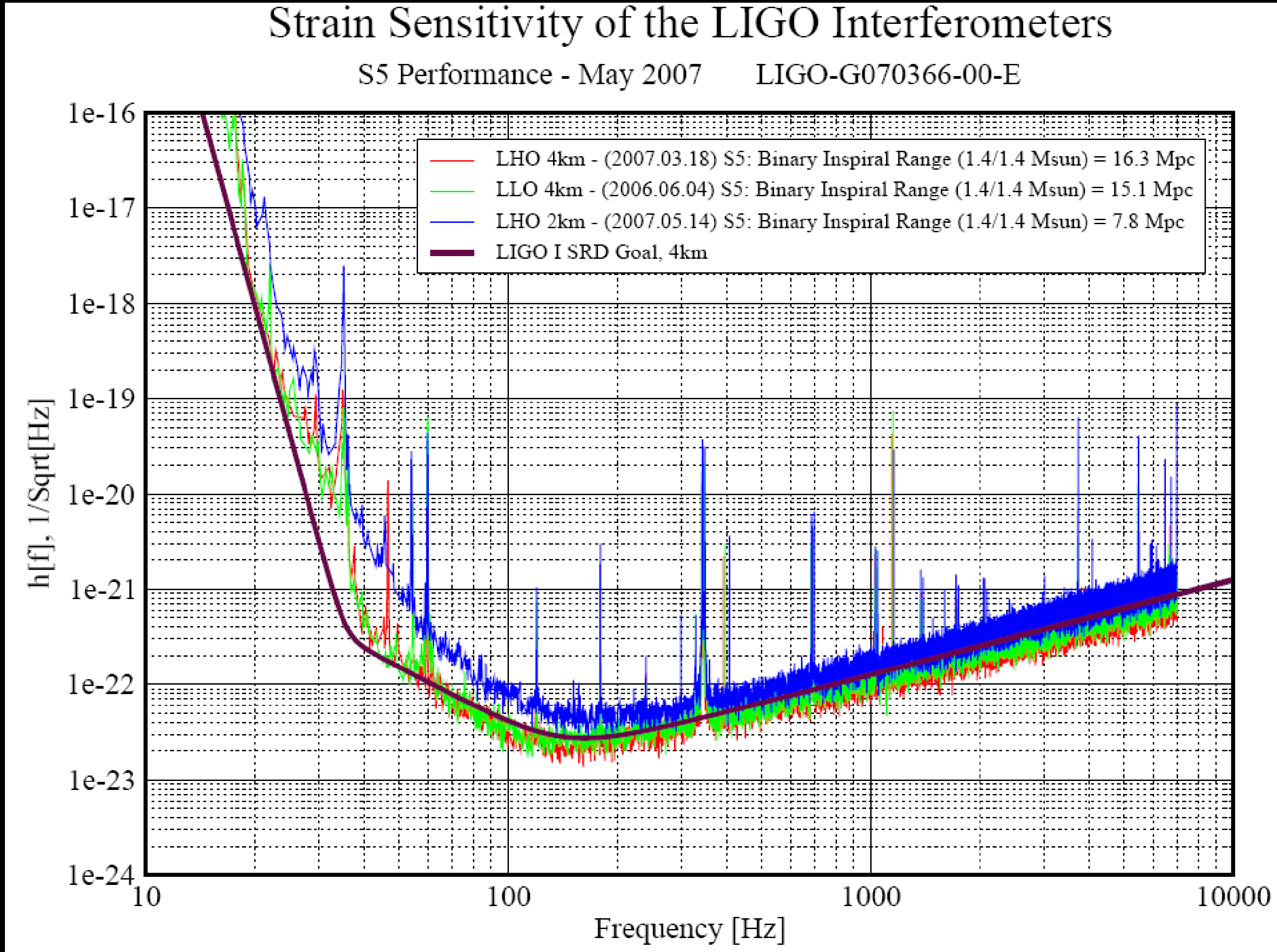
Timeline of GW searches to 2011



Gravitational Wave Network Sensitivity



LIGO design sensitivity reached in S5

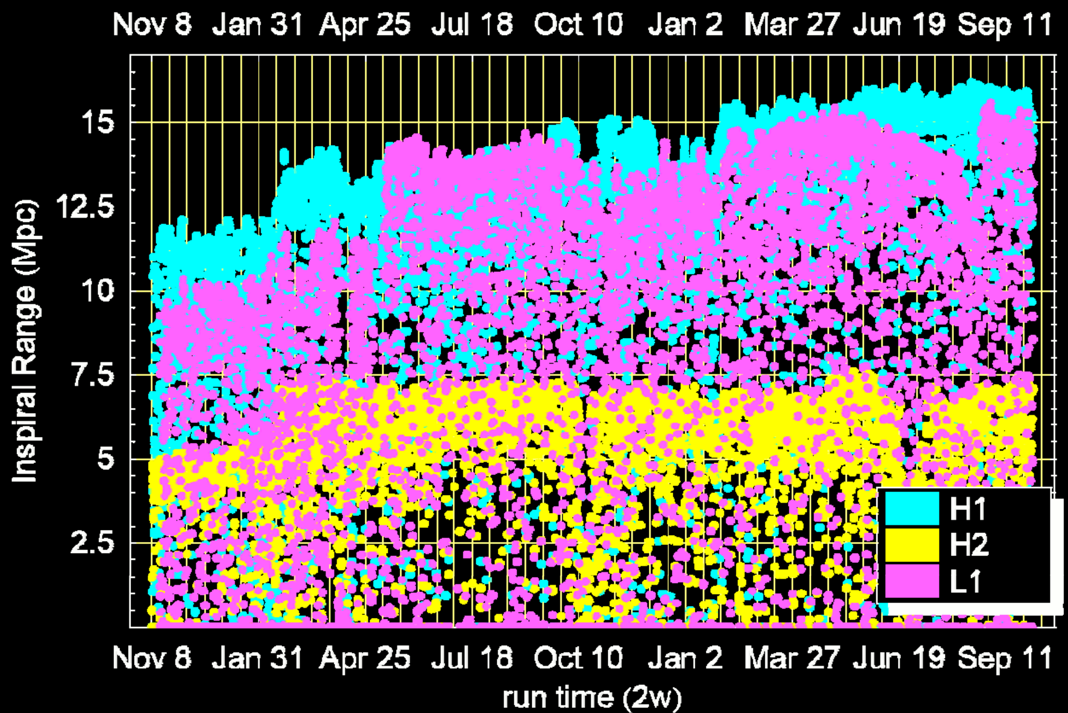


Astrophysical searches

- Six science runs to date involving LIGO, GEO and recently VIRGO (approaching 50 publications)
- Continuous waves
  - Rapidly rotating deformed neutron stars
    - Known radio pulsars (using radio and X-ray observations to provide signal phase) and unknown sources
  - Coherent and semi-coherent searches
  - Targeted (supernova remnants, globular clusters, galactic centre, X-ray sources) and all-sky searches
- Compact binary coalescences
  - late stage neutron star or black hole binary inspirals, mergers and ring-downs
- Transient searches
  - Coincident excess power from short duration transient sources
  - External triggers: GRBs, X-ray transients, radio transients, supernova, neutrino observations
- Stochastic background
  - Cosmological i.e. from inflation
  - Combined background of astrophysical sources

LSC Fifth science run (S5) – VSR 1

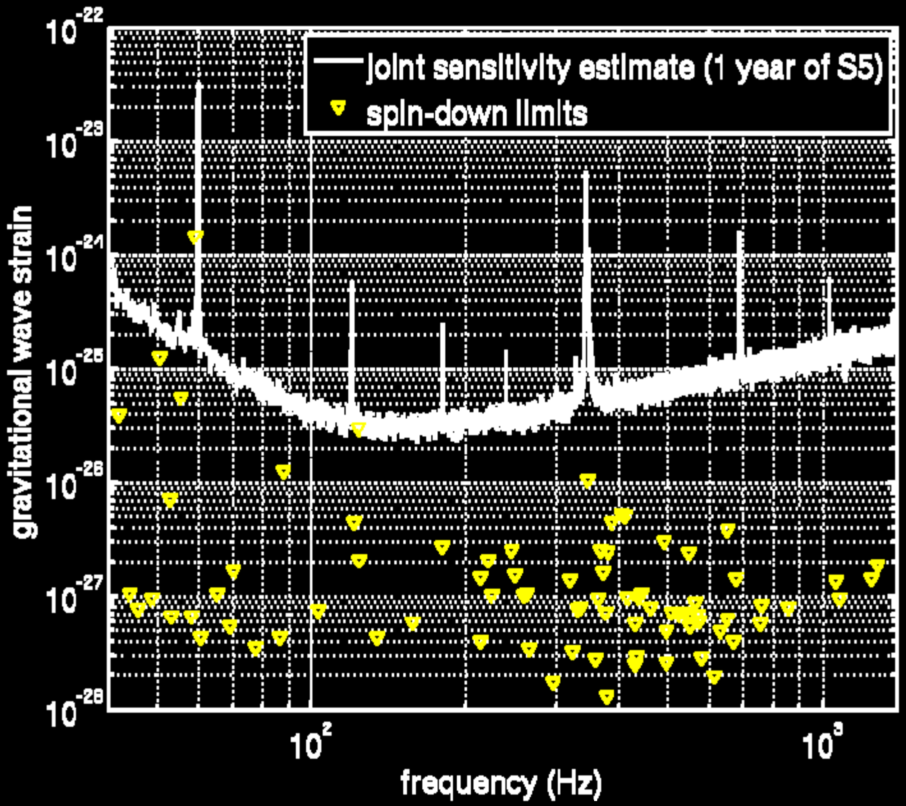
- S5 started in Nov 2005 and ended Oct 2007
  - LIGO collected 1 year of triple coincidence data at design sensitivity
  - Duty cycle: ~75% per interferometer, 53% triple coincidence
- GEO joined
  - in overnight & weekend mode January 20th 2006
  - in 24/7 mode May 1st 2006 (Duty cycle: ~91%)
  - back in overnight & weekend mode Oct. 2006 – Oct. 2007
- VIRGO joint May 18th 2007 (VSR1)
  - Duty cycle: 81%



- A figure of merit is the range to which a NS/NS binary (1.4 $M_\odot$) is seen at SNR of 8
  - LIGO: 4km range 15 Mpc, 2km range 7 Mpc
  - VIRGO: range 4 Mpc

Crab pulsar search

- Known pulsars provide a well defined target for GW searches
- Crab pulsar has largest spin-down rate of any known radio pulsar at 3.7×10^{-10} Hz/s
- Assuming all energy is dissipated by GW emission we can set a spin-down upper limit on the strain at 1.4×10^{-24} ($Izz = I_{38} = 10^{38}$ kgm^2, r=2 kpc)
  - largest for any pulsar within the band and beatable with several months of LIGO fifth science run data (S5)
- Nebula emission and acceleration are powered by the spin-down, but uncertainties in the error budget could leave ~80% of the available energy unaccounted for



An estimate of the joint LIGO sensitivity for known pulsar searches using 1 year S5 data, and spin down upper limits for known millisecond pulsars

Abbott et al, Ap. J. Lett. 683 (2008) 45

Crab pulsar search

- Using 9 months of combined LIGO S5 data no GW signal from the Crab pulsar was seen, but…
  - We have a limit on the GW amplitude of h_0 = 3.4x10^{-25} - a factor of 4.2 lower than the classical spin-down limit
  - The ellipticity result of 1.8x10^{-4} is into the range permitted by some exotic quark star equations of state (Owen, *Phys. Rev. Lett*, 2004, Lin, *Phys. Rev. D*, 2007, Haskell et al, *Phys. Rev. Lett*., 2007)
  - Constrains the amount of the available spin-down power radiated away via GWs to less than 6%
  - Observational constraints of pulsar orientation (Ng and Romani, *Ap. J*., 2007) can be used and improve our limit to be 5.3 times lower than spin-down
  - Pulsar's braking index of n=2.5 shows that pure GW emission is not responsible for spin-down (n=5), and from this Palomba (*A&A,* 2000) suggest a spin-down limit 2.5 times lower than the classical one – still beaten by our result
- Represents new regime being probed only through GW observations

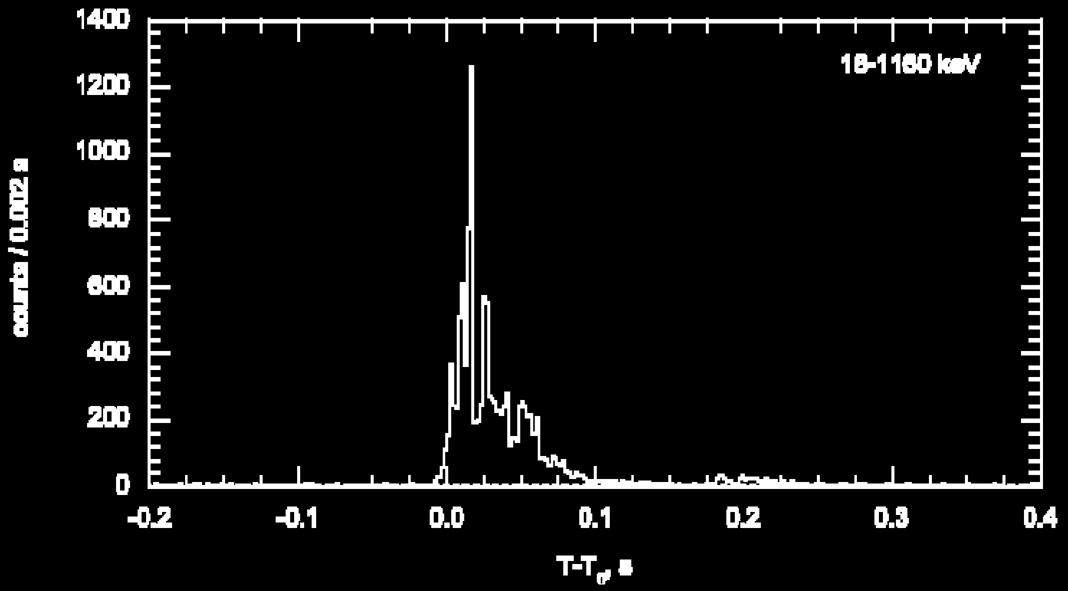
Credit: NASA/CXC/SAO

Triggered searches

- 213 GRB triggers during S5 (mainly from Swift, INTEGRAL, IPN, HETE-2)
  - time and positional information for GW search
  - more confidence in detection (eventually) and allows more source information to be extracted

Abbott et al, Astrophys. J. 681 (2008) 1419

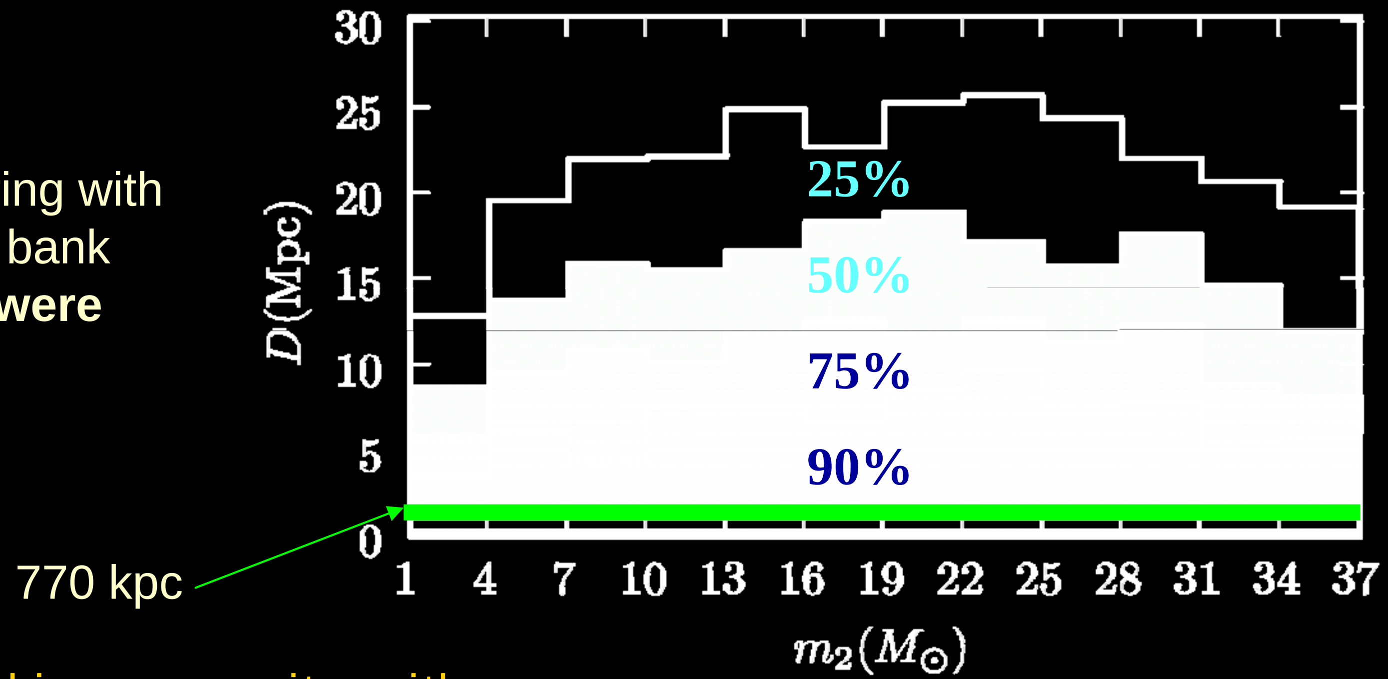
Detected by Konus-Wind, INTEGRAL, Swift, MESSENGER



- Particularly interesting short, hard event, GRB070201, observed with a position coincident with spiral arms of M31 – distance 770 kpc
- Possible progenitors for short GRBs:
  - NS/NS or NS/BH mergers: Emits strong gravitational waves
  - Soft gamma-ray repeater (SGR): May emit GWs, but weaker

GRB070201 model based inspiral search

Using matched filtering with an inspiral template bank **no plausible GWs were identified**



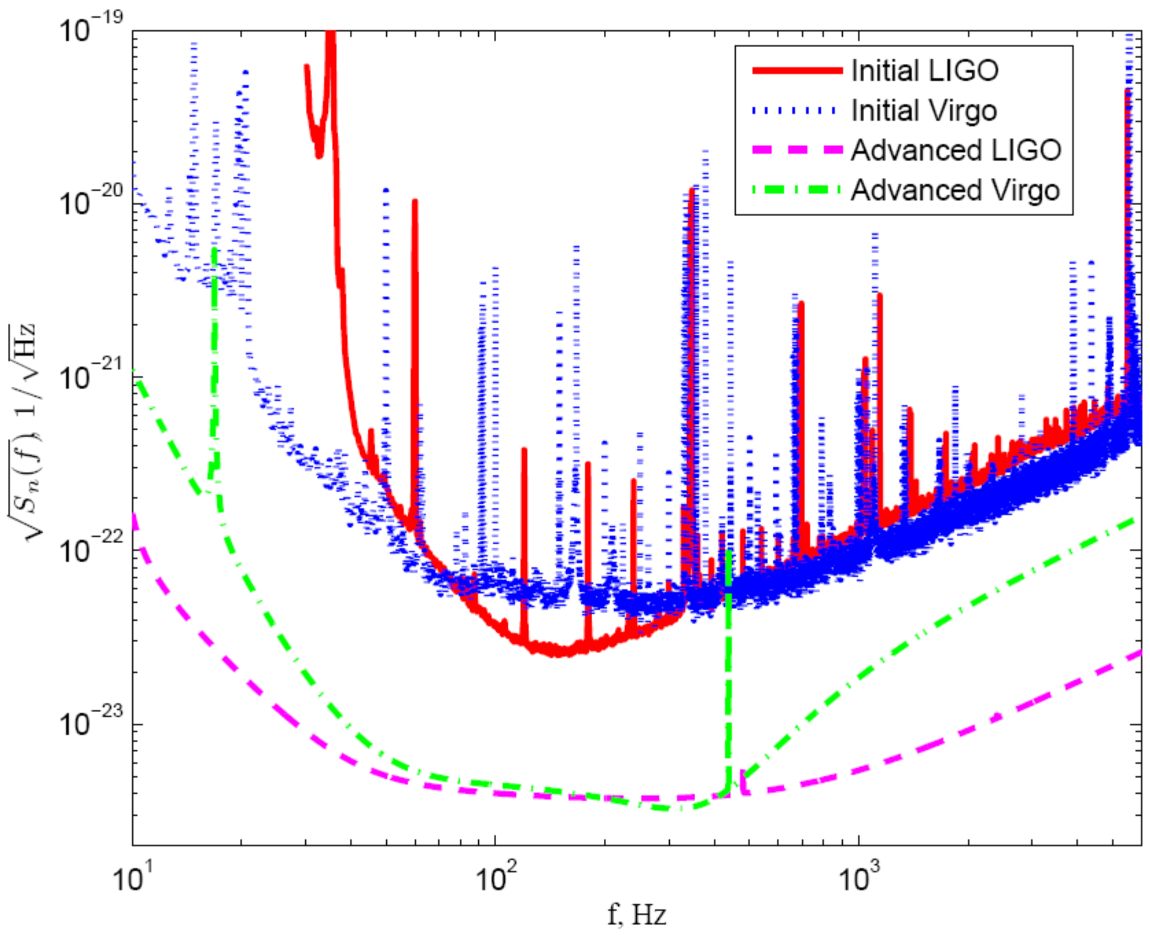
- Exclude compact binary progenitor with masses
  - 1 $M_\odot$ < m_1 < 3 $M_\odot$ and 1 $M_\odot$ < m_2 < 40 $M_\odot$ with D < 3.5 Mpc away at 90% CL
- Exclude any compact binary progenitor in our simulation space
  - at the distance of M31 at > 99% confidence level

GRB070201 SGR search

- A hypothesised model for the GRB is an Soft Gamma Repeater (SGR) giant flare
- Energy release in γ-rays is consistent with SGR model
  - measured γ-ray fluence = 2 x 10^{-5} ergs/cm^2 (Konus-Wind)
  - Corresponding γ-ray energy, assuming isotropic emission, with source at 770 kpc (M31): ~10^{45} ergs
  - SGR models predict energy release in GW to be no more than ~10^{46} ergs

Limits on GW energy release from GRB 070201 are consistent with an SGR model in M31 (can not exclude it)

Planned detector evolution



Most probable rate of binary black hole coalescences detectable by the LIGO system ~ 1/4 - 1/600 years

Thus detection at the sensitivity level of the initial detectors is not guaranteed

Need another X 10 to 15
then rate of detectable black hole coalescences :
~ 10s to 100s per year

(See J. Abadie et al "Predictions for the Rates of Compact Binary Coalescences Observable by Ground-based Gravitational-wave Detectors",arXiv:1003.2480; submitted to CQG)

x10 better amplitude sensitivity
⇒ x1000 rate=(reach)3
⇒ 1 year of Initial LIGO
< 1 day of Advanced LIGO

Figure from Abadie et al. For aLIGO design sensitivity see LIGO-T0900288-v3

As a step on the way:

- LIGO and Virgo
  - 2007 - 2009 incremental detector enhancements

    Enhanced LIGO:

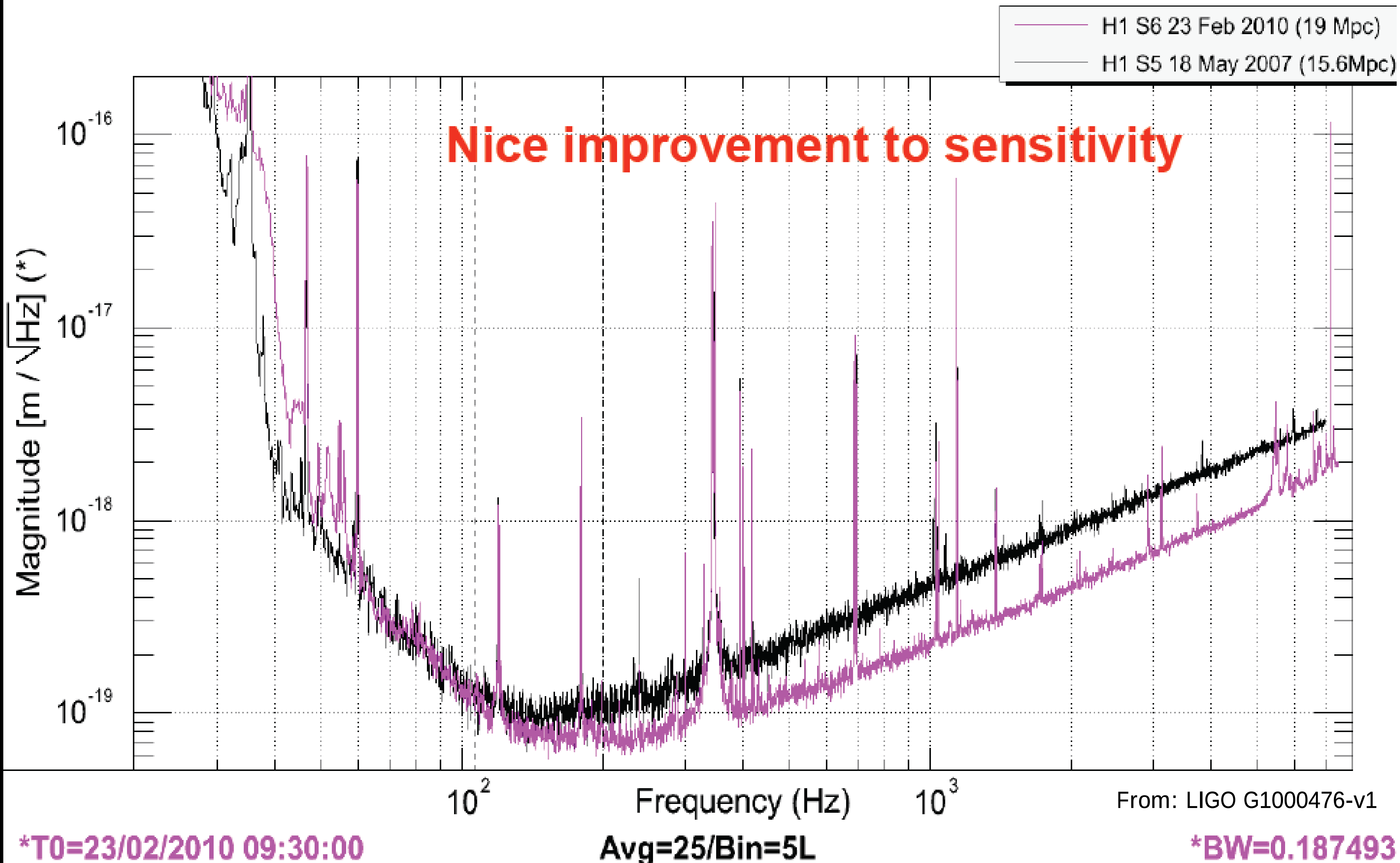
    higher laser power, better optical readout, higher power optics

    VIRGO +

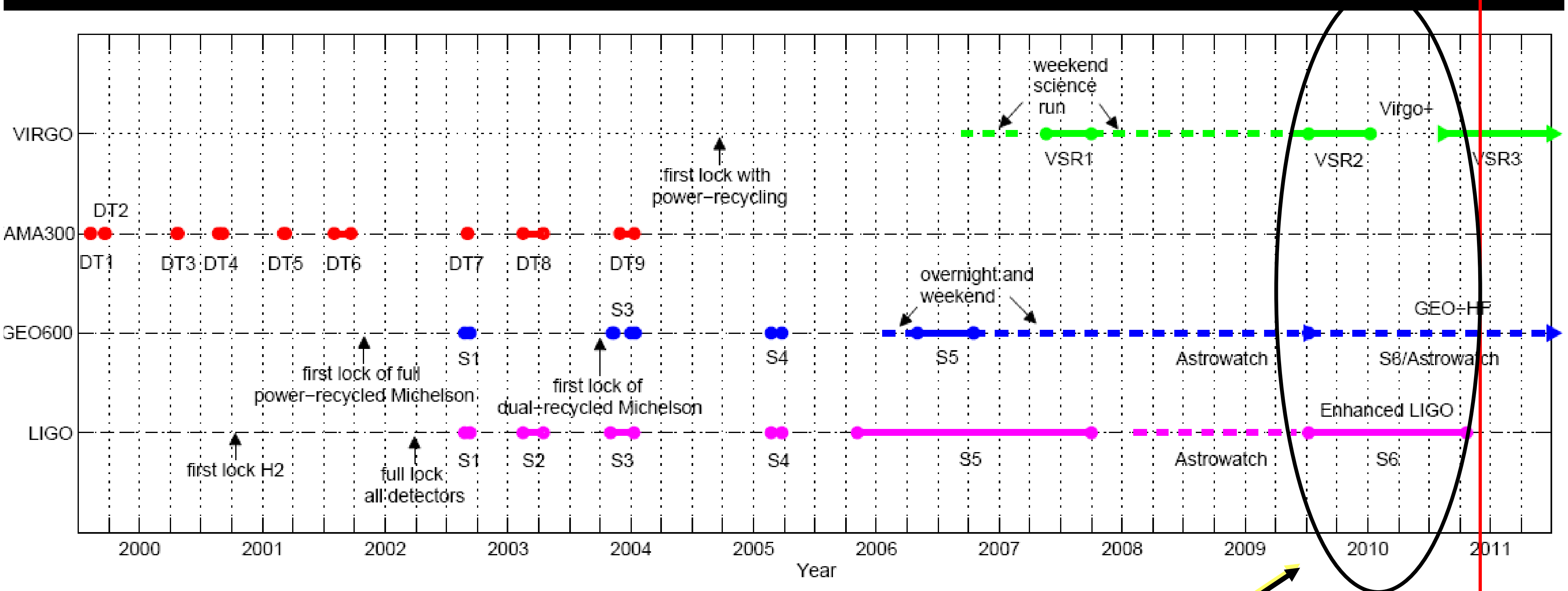
    higher laser power, and silica suspensions to reduce thermal noise, better optical readout

GEO + LIGO H2 + bar detectors maintained ‘Astrowatch’ until early 2009 when enhanced detectors started operation.

Enhanced LIGO



Timeline of GW searches to 2011



Data analysis ongoing

We are here

Status of Advanced detectors

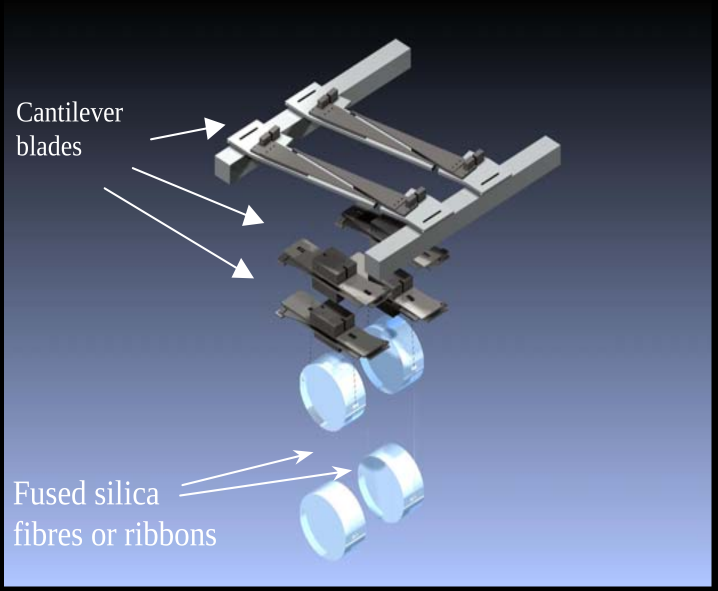
- Advanced LIGO
- Advanced Virgo
- GEO-HF
- Large Cryogenic Gravitational Telescope (LCGT)

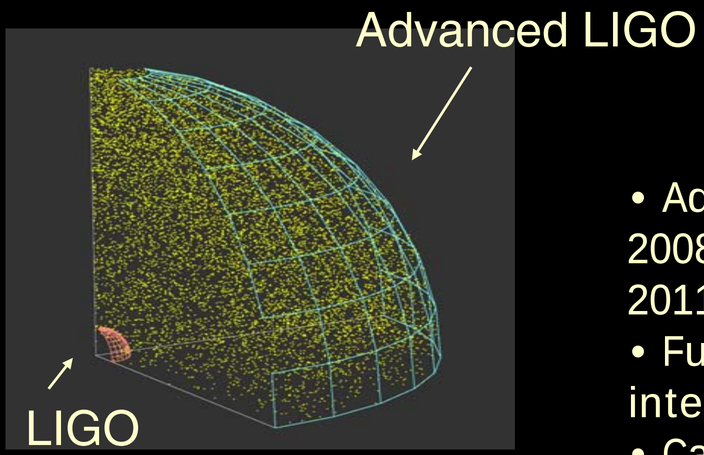
Advanced LIGO

Achieve x10 to x15 sensitivity improvement:

Key GEO technology being applied to LIGO
- silica suspensions (UK)
- more sophisticated interferometry
- more powerful lasers (Hannover)

Plus active isolation, high power optics and other input from US groups and the LSC





- Advanced LIGO Project Start approved from 1 April 2008 in USA to allow re-construction on site starting 2011
- Full installation and initial operation of 3 interferometers by 2014/5
- Capital contributions funded in UK and Germany (PPARC/STFC and an equivalent amount from MPG)

- Project is making excellent progress

‘LIGO-Australia’

- Goal–
  - a southern hemisphere interferometer early in the Advanced LIGO & Advanced Virgo operating era
  - Install one of the Advanced LIGO IFOs planned for Hanford into infrastructure in Australia provided by Australia for possible detector operation in 2017

- In-principle approval from NSF
- Australian proposal for construction funds currently being written

Determination of Source Sky Position

Modeled Sources

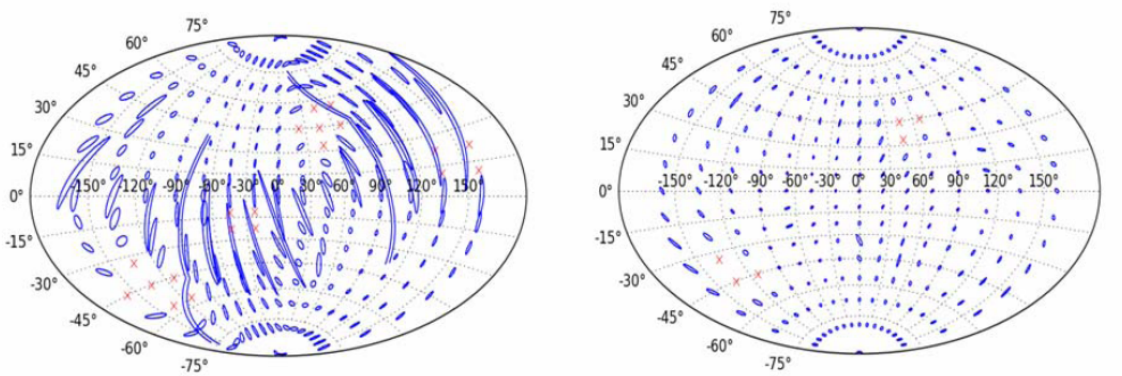


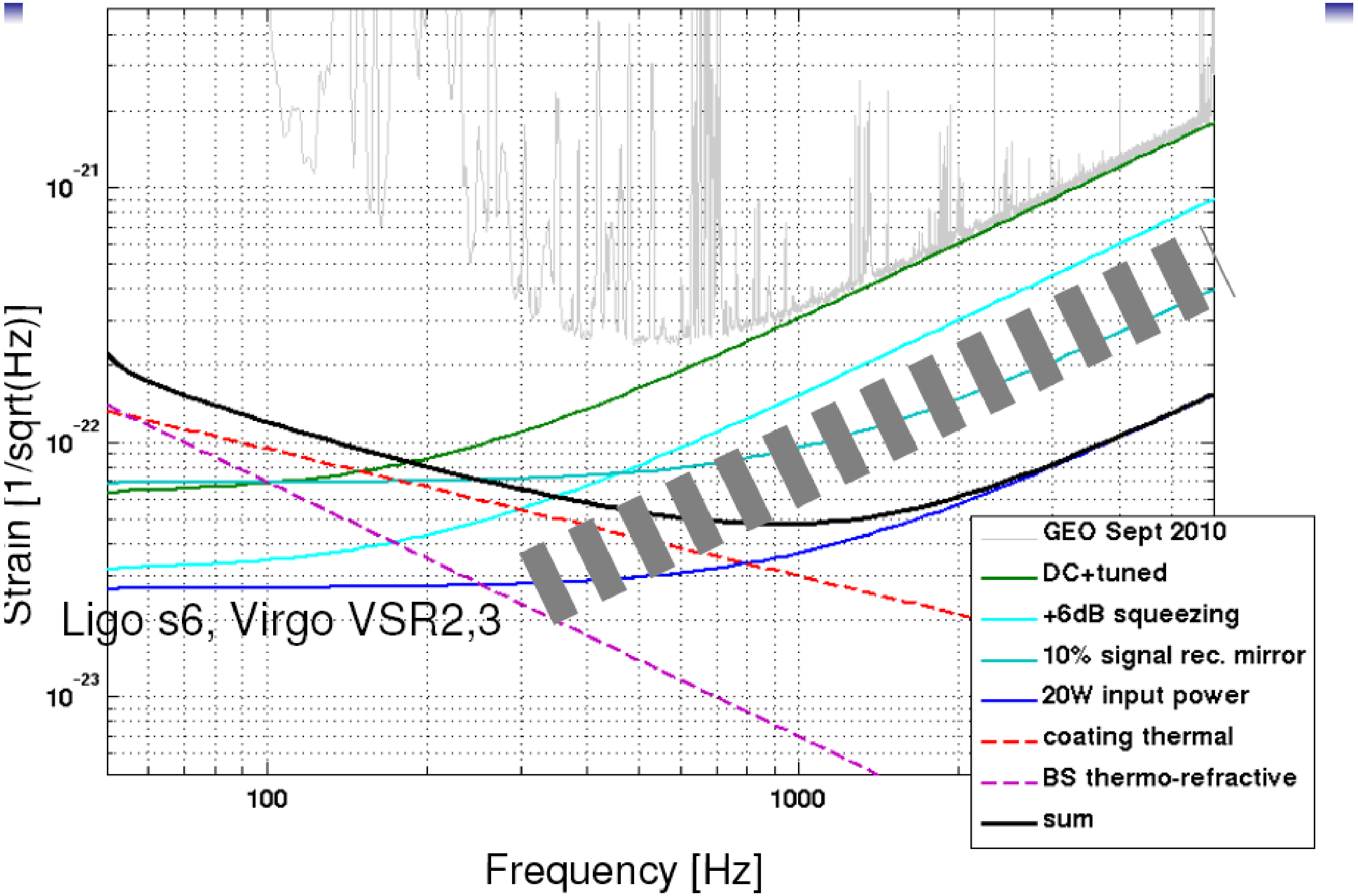
Figure 5 Left: Sky localization with the HHLV network. Right: Sky localization with the AHLV network. The plots show the 90% confidence contours for binary NS sources face on and at a horizon distance of 200Mpc. The plot assumes that the advanced detectors would achieve a SNR =8 for these sources at a horizon distance of 180Mpc. The red X’s are points in the sky where the signal would be poorly detected with a network combined SNR < 12 .

Figure from: LIGO-DOC: T1000251

Advanced Virgo

- Implementation will start 2011
- Hardware upgrades (laser power, optics, coatings, suspensions and others) will be installed
- Re-commissioning period will be 2012-2013
- Operation on same timescale as Advanced LIGO

GEO-HF



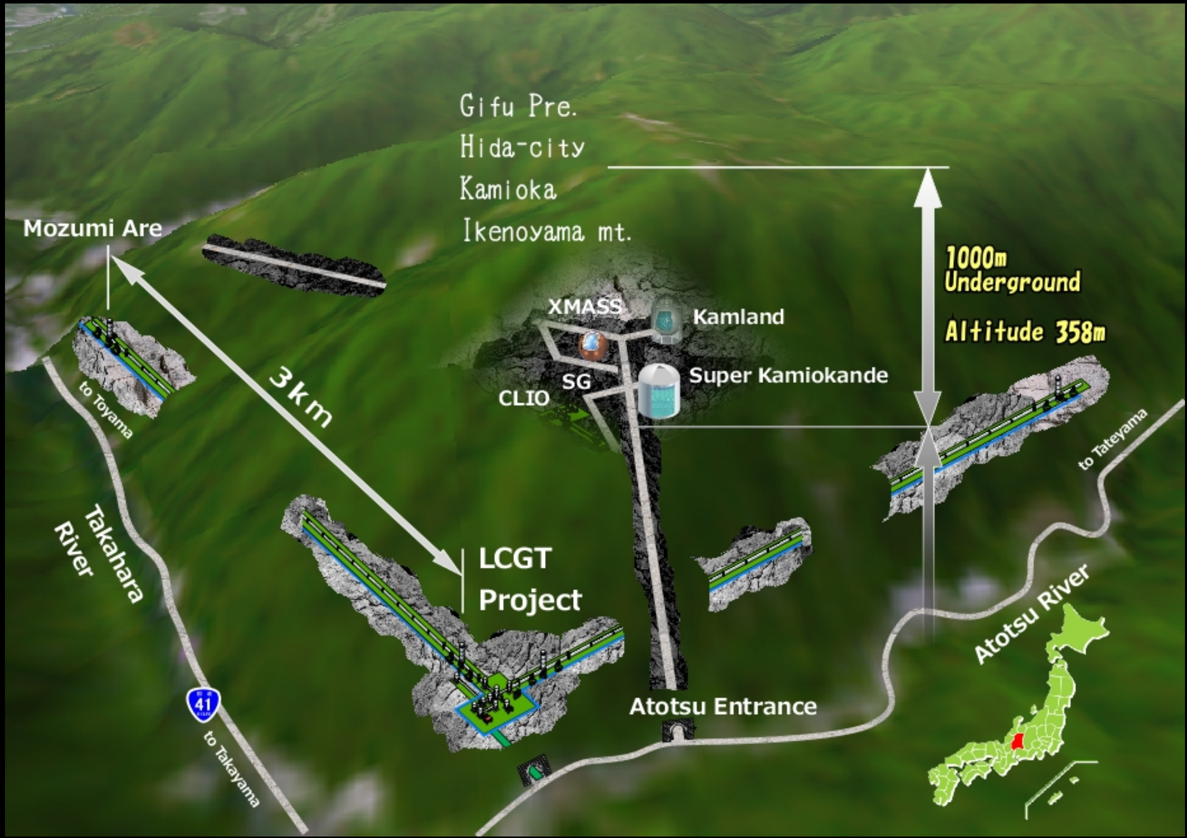
GEO being upgraded with dual purpose

- target high frequency (HF) signals
- demonstration of new technologies

Aim for sensitivity improvements at frequencies >500Hz

Noise reduction of ~3.4dB already demonstrated

Large **Cryogenic** Gravitational Telescope (LCGT) (Japan)



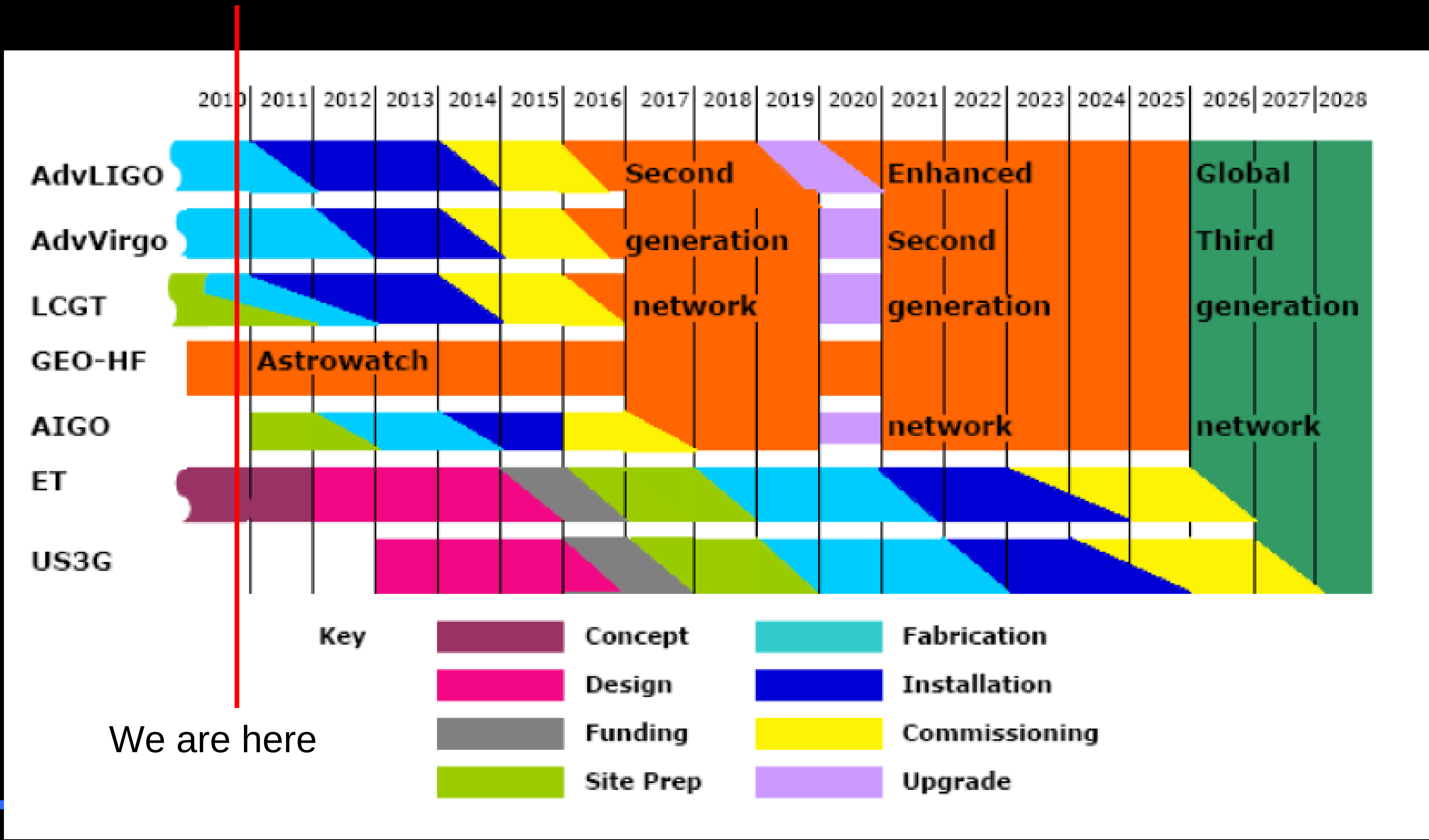
June, 2010: Japanese government approved initial funds for construction of LCGT
Planned for construction in the Kamioka mine in Japan

Initial LCGT without cryogenic operation will be operated by October 2014, as an engineering demonstration

Initial LCGT forms the main part of Baseline LCGT (except recycling and cryogenics)

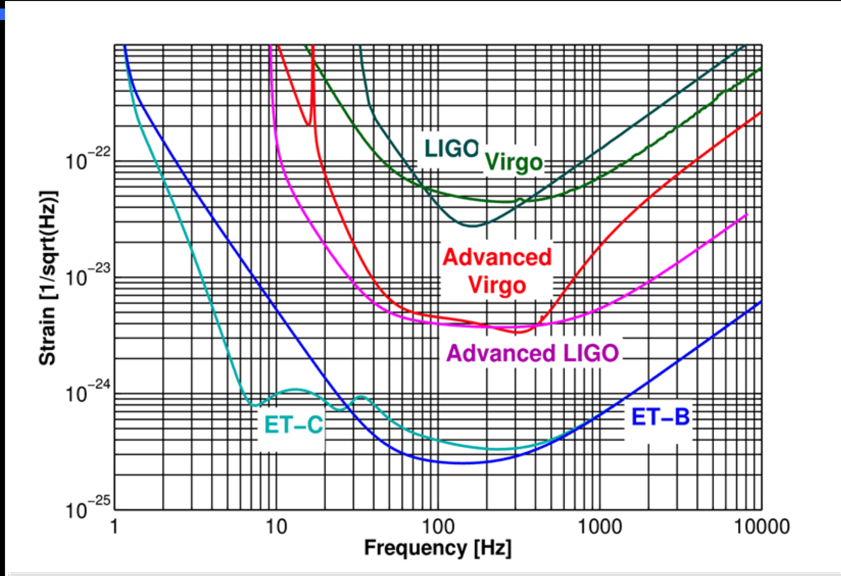
Sensitivity goals very similar to Advanced LIGO and Advanced VIRGO

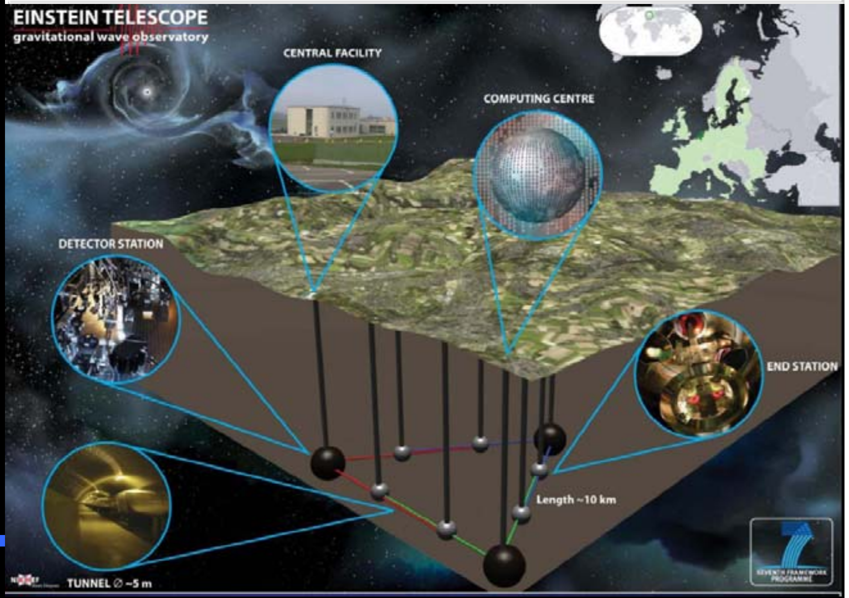
The worldwide GW roadmap



Challenges of the field for 3rd Generation

- For a further factor of ten sensitivity improvement we need to
  - fully understand and further reduce seismic and thermal noise from mirrors and suspensions
  - improve interferometric techniques to reduce the significance of quantum noise in the optical system
  - refine data analysis techniques
- A design study for such a detector [the Einstein gravitational-wave Telescope – 'ET'] has now been funded by the EC under FP 7
- R&D relevant for 3rd generation sensitivities proceeding in the US





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The Network of Gravitational Wave Facilities

- 1st generation network on ground completed data taking
- 2nd generation follows 2010-14, designs mature,
  - Advanced LIGO (USA/GEO/LSC)
  - Advanced VIRGO (Italy/France/Netherlands
  - Large Cryogenic Gravitational Telescope (LCGT) (Japan)
  - GEO-HF (GEO/LSC)
- 3rd generation
  - Lab research underway around the globe
  - Plans for a design proposal under FP7 framework for a 3rd generation detector in Europe
- LISA – spaced based detector
  - See talk by Paul McNamara